

Characterization Of CPV Arrays Based On Differences On Their Thermal Resistances

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Abstract. Thermal characterization of Concentrating Photovoltaics (CPV) modules and arrays is needed to determine their performance and modelling of energy forecast. Module-ambient thermal resistance is easily obtained from its definition but the cell-module thermal resistant needs to be estimated from indirect procedures, two of them are presented in this paper. In addition, an equivalent parameter is defined, the Concentrator Nominal Operating Module/Cell Temperature (CNOMT/CNOCT), the temperature at Concentrator Standard Operating Conditions (CSOC). Definitions and expression to relate (CNOMT/CNOCT) to thermal resistances are presented, plus several examples of estimations from real operating arrays.

INTRODUCTION

The aim of this work is to describe a procedure for the characterization of the thermal resistances of a CPV module, with the final objective of determining the cell temperature and relating it to ambient operating conditions. A major difficulty in CPV technology is that cell temperature cannot be directly measured because of inherent characteristics of this technology such as concentrated high flux, small cell sizes and high thermal gradients, both in horizontal and vertical dimensions. The compactness of the receivers, which consist not only of the cell but also of the means for heat spreading, electrical insulation and connections, secondary optics,..., hinders the placement of sensors as close as necessary to the cell.

This difficulty has been solved by means of indirect methods which are based on the relationship between the cell temperature and other parameters. The open circuit voltage is strongly related to cell temperature and has been widely used to determine cell temperature variations. Nevertheless, while temperature variations can be easily related to V_{oc} changes through the voltage temperature coefficient, β , obtaining the dependence between the absolute value of the cell temperature and V_{oc} is a very difficult task. Several methods [1-4] have been proposed based on dark IV measurements, electroluminescence or simply direct characterization carried out on the cell level. But V_{oc} is also affected by other operating conditions such as non-uniform light distribution, chromatic aberration, spectrum... which cannot be reproduced in

any of these methods and leads to significant uncertainties in cell temperature.

EQUIVALENT THERMAL CIRCUIT

Heat flow is commonly modelled with an electrical circuit where thermal resistances are substituted by resistors and thermal capacitances by capacitors. In CPV, since the input of power to a CPV module is direct normal irradiance (DNI), whose dimensions are W/m^2 , it is more practical to define its thermal resistances per unit of area ($^{\circ}C/(W/m^2)$) instead of the absolute value ($^{\circ}C/W$). In this way, it is simple and direct to compare different CPV technologies according to their thermal properties.

In CPV, heat exchange is deeply dominated by thermal conduction between the cell and the heat-sink of the module, which in many cases is simply a flat metal or glass sheet which constitutes the rear side of the housing, and by convection and radiation between such heat-sink and the ambient. Consequently, a simple thermal circuit of a CPV module or systems consists of only on two thermal resistances in steady state condition. This approach is accurate enough to relate the cell temperature to ambient conditions.

Besides cell and ambient temperature, an intermediate temperature called module or heat-sink temperature is commonly defined as the temperature at the rear plate or heat-sink of the module. Unlike cell temperature, module temperature can be directly measured. In the rear plate or heat-sink temperatures

are highly non-uniform, so the sensor must be placed in the plate or heat-sink core just behind a cell position, in such a way that the $T_{cell} - T_{mod}$ difference is caused only by the vertical temperature drop through the stack of different materials. Besides, there can be significant differences in the module temperature throughout the cells [5], so it is convenient to measure in more than one cell and average them.

The two thermal resistances relate these three temperatures: $R_{th\ c_m}$ between cell and module and $R_{th\ m_a}$ between module and ambient, this last being highly dependent on wind (see figure 1).

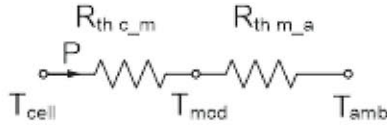


FIGURE 1. Equivalent thermal circuit of a CPV module or systems at steady state condition.

Summarizing, module temperature provides an intermediate point between cell temperature and ambient, it being strongly related to cell temperature by heat conduction.

Heat power (P) to be dissipated is related to DNI. Nevertheless part of the incident irradiance is not transmitted by the lens (see Fig. 2), accounted by the optical efficiency (η_{op}) and another part is converted by the cell into electricity (η_{cell}). Consequently heat power is defined as:

$$P = B \cdot \eta_{op} (1 - \eta_{cell}) = B \cdot (\eta_{op} - \eta_{DC}) \quad (1)$$

where $\eta_{DC} = \eta_{op} \cdot \eta_{cell}$ is the DC efficiency of the CPV module and B is the incoming irradiance.

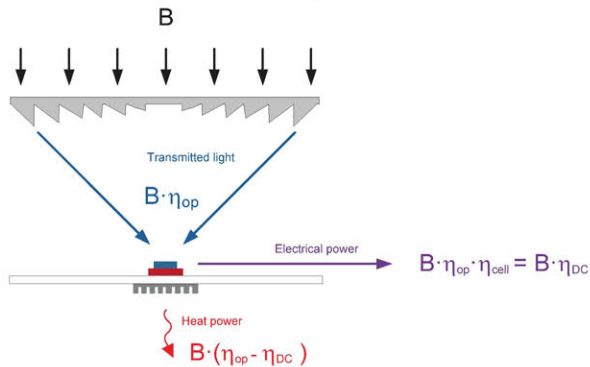


FIGURE 2. Power balance in a CPV module; heat power depends on incoming irradiance (B), optical efficiency (η_{op}) and electrical efficiency of the module (η_{DC}) defined as the product of η_{op} and the cell efficiency (η_{cell}).

The thermal resistances of the CPV thermal model are obtained by dividing the temperature (ΔT) drop by the heat power (P) dissipated by the cell.

$$R_{th} = \frac{\Delta T}{B \cdot (\eta_{op} - \eta_{DC})} \quad (2)$$

Temperature Sensors

To measure module temperature, a sensor must be placed preferably without module modification. A few points are advisable to reduce at minimum the influence of the sensor:

- Placed at rear panel or heat-sink core, just behind and as close as possible to the cell.
- More than one sensor is recommended, to obtain a more representative value from the entire module.
- Sensor should be smaller than the cell size (Thermocouple, PT100...)
- It should have the minim additional thermal resistance due to the sensor itself, so it is recommended that a thin film surface mount type sensor be used, attached with thermal glue/paste and fixed with adhesive tape.

R_{TH} MODULE-AMBIENT

The thermal resistance between module and ambient ($R_{th\ m_a}$) can be directly obtained through the expression:

$$T_{mod} = T_{amb} + P \cdot R_{th\ m_a} \quad (3)$$

which requires data acquisition of DNI, T_{mod} and T_{amb} for a long time, commonly covering several periods at different ambient temperatures and wind speeds. Appropriate data filtering must be applied to reject any thermal transient caused by clouds, rejecting periods of at least 20 minutes subsequent to any DNI deep change.

Concentration Nominal Operation Module Temperature (CNOMT)

The Concentrator Nominal Operating Module Temperature is defined as the module temperature at Concentrator Standard Operating Conditions (CSOC, $B=900 \text{ W/m}^2$, ambient temperature= $20 \text{ }^\circ\text{C}$, wind speed= 2 m/s , Spectrum: Direct normal AM1.5) as defined in [6].

If CNOMT is known, module temperature can be obtained from operating ambient conditions by means of the following expression:

$$T_{mod} = T_{amb} + \frac{CNOMT - 20}{900} \cdot B \quad (4)$$

Both expressions (3) and (4) are then equivalent for a given wind condition, in this case 2 m/s, and are related by the formula:

$$\frac{CNOMT - 20}{900} = R_{th\ m_a} (\eta_{op} - \eta_{DC}) \quad (5)$$

Figure 4 shows an example case of a CPV module characterization. Regression lines (Fig. 3) are obtained fixing the slope to 1 and the values of $R_{th\ m_a}$ and CNOMT are obtained by eq. (3) or (4).

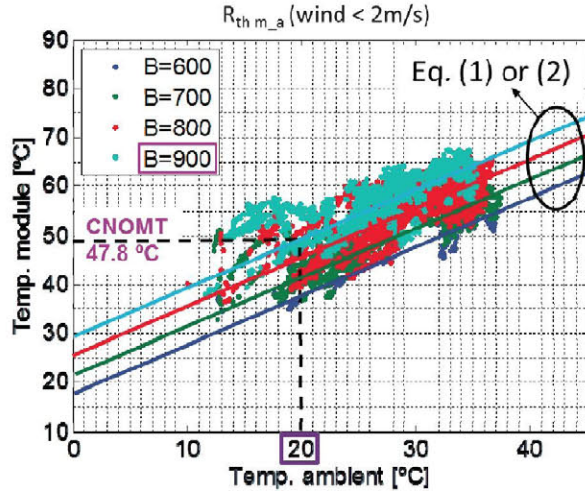


FIGURE 3. Module temperature (Type A – Table 1) as a function of ambient temperature and DNI as parameter in intervals of 100 W/m² (i.e. 700 W/m² stands for 650-750 W/m²); wind filter: < 2m/s; CNOMT is obtained for CSOC conditions. R²=88, 86, 88 and 88 % and y-intercept=17, 21, 25 and 30 °C respectively.

A comparison of the CNOMT obtained for three HCPV modules (details in table 1) is shown in Figure 4. Tight data filtering has been applied to fulfil CSOC conditions. SMR has been used to filter the spectrum [7]

TABLE 1. CPV technologies measured and compared

Type	Concentration	Heat-sink	NOMT
A	820 X	2 mm rear flat plate	47.8 °C
B	820 X	4 mm rear flat plate	44.1 °C
C	1300 X	Aluminum heat-sink	48.2 °C

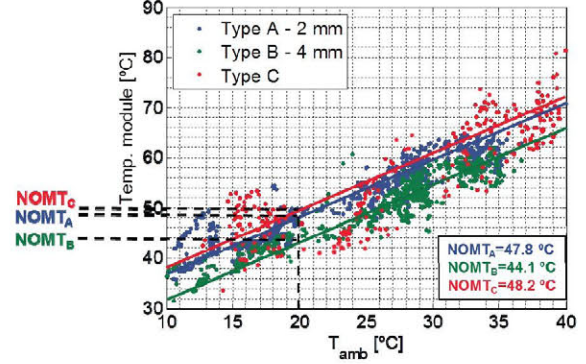


FIGURE 4. Module versus ambient temperature of three different technologies. (Data filtering: DNI = 900 ± 50 W/m², wind < 2m/s, SMR = 1 ± 0.05)

Wind Effect On Rth Module-Ambient

By applying several filters, influence of wind on $R_{th\ m_a}$ can be determined. Wind effect depends not only on speed but also on relative direction to the module normal [8] which can increase data dispersion and uncertainty. Nevertheless, with long term characterization it is possible to obtain high correlation between ambient and module temperature as a function of wind speed. Figure 5 shows the result for type A technology and Figure 6 the evolution of the thermal resistances for the three technologies.

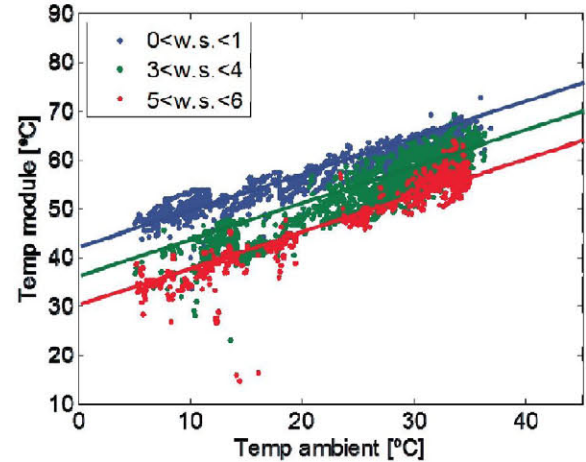


FIGURE 5. Module versus ambient temperature of Type A technology for three wind speeds (data filtering: DNI = 900 ± 50 W/m², SMR = 1 ± 0.05). $R_{th\ m_a}$ dependence on wind can be obtained with regression lines and eq. (3). R²=79, 80 and 70 % respectively.

A simple linear fit can be obtained for low wind speeds (< 6 m/s):

$$R_{th} = R_{th0} (1 - a \cdot V_{wind}) \quad (6)$$

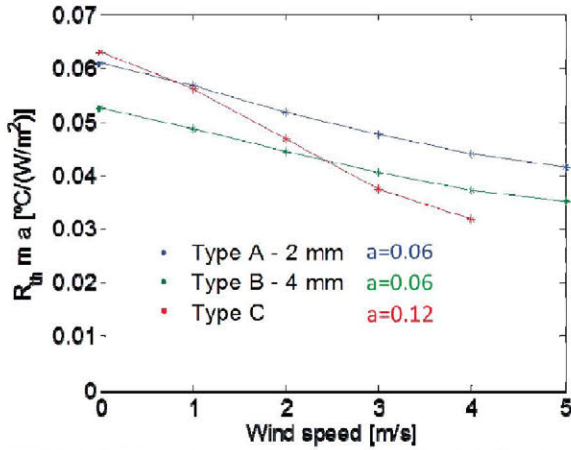


FIGURE 6. Dependence of the $R_{th\ m_a}$ with wind for three CPV module technologies.

It can be observed that Type A and B technologies, identical except for the thickness of the backplane (2 and 4 mm respectively), have the same wind dependence, while Type C, based on an aluminum heat-sink has a higher slope and thermal improvement with higher wind speeds.

R_{TH} CELL-MODULE

In this section two procedures are explored to obtain the thermal resistance between the cell and the module temperature defined in previous section.

Indoors-Outdoors V_{oc} Comparison

The procedure consists of the comparison of the V_{oc} of a CPV module measured indoors with a solar simulator (as the Helios 3198 [9]) and outdoors at similar incoming irradiances. On the one hand, indoor measurement is done at a known cell temperature $T_{cel(in)}$ since the flash light lasts just a few milliseconds and does not heat up the cell. On the other hand, outdoor cell temperature $T_{cel(out)}$ can be determined if β is known [2] by means of the expression:

$$T_{cel(out)} = T_{cel(in)} + \frac{\Delta V_{oc} / N_s + n \cdot V_t \ln \frac{I_{out}}{I_{in}}}{\beta} \quad (7)$$

where ΔV_{oc} stands for the V_{oc} difference between indoor and outdoor measurements, n is the ideality factor, V_t is the thermal voltage, N_s is the number of cells connected in series, β is dV_{oc}/dT , and I_{out} and I_{in} are the respective short circuit currents.

Once outdoors cell temperature is determined, outdoor module temperature $T_{module(out)}$ is also needed

to obtain $R_{th\ c_m}$ by means of eq. (1), where $\Delta T = T_{module(out)} - T_{cel(out)}$.

Even though both measurements were carried out at exactly the same irradiance B and spectral condition (fixed by SMR), most probably short circuit currents will not be equal because of its strong dependence on lens temperature [10-12] so the current correction included in eq. (7) would be needed. This lens temperature variation leads to differences in color distribution which can also affect V_{oc} and increase uncertainty.

Mesh Grid Procedure

Using a similar translating relationship, the value of the $R_{th\ c_m}$ can be estimated using two identical modules outdoors at the V_{oc} condition in a side-by-side comparison. The two modules should be placed on the same tracker, being then under the same ambient conditions, one of them covered by a mesh neutral filter that reduces the irradiance. Module temperatures and V_{oc} of both modules must be recorded after the initial thermal transient period of 15-20 min caused by the module thermal capacitances (see Fig. 7) and the thermal resistance can be obtained according to eq. (8).

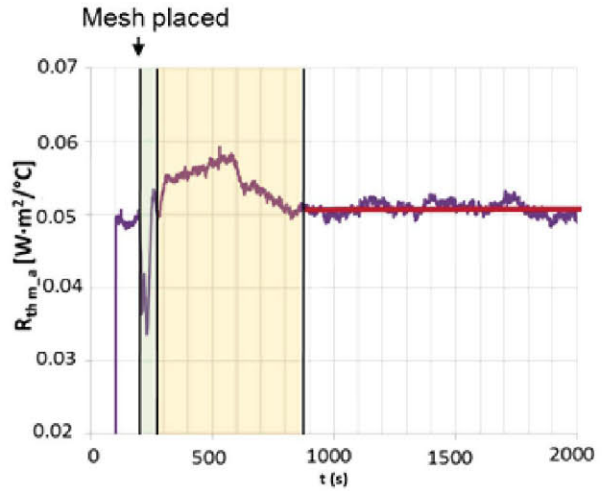


FIGURE 7. The graph shows the initial thermal transient, caused by the thermal capacitances of the module, after a mesh filter of 60% transmission is placed on one of the CPV modules of Type A. The red line shows the average $R_{th\ c_m}$ obtained during a steady state period of 1000 s.

$$R_{th\ cel_mod} = \frac{\frac{\Delta V_{oc} / N_s + n \cdot V_t \ln(T_{filter})}{\beta} - \Delta T_{mod}}{\Delta P} \quad (8)$$

where ΔV_{oc} and ΔT_{mod} stands for the V_{oc} and module temperature difference respectively between both modules, T_{filter} is the transmission of the mesh filter (50-70% values are recommended) and ΔP is the heat power variation between both modules, i.e., $\Delta P = B \cdot (1 - T_{filter}) \cdot \eta_{op}$ where B stands for the incoming irradiance.

Concentrator Nominal Operating Cell Temperature (CNOCT)

Similarly to CNOMT, it can be defined the Concentrator Nominal Operating Module Cell (CNOCT), as the cell temperature at CSOC.

The value of CNOCT is related to CNOMT by the $R_{th\ c_m}$, as expressed in eq. (9).

$$CNOCT = CNOMT + 900 \cdot R_{th\ c_m} \cdot (\eta_{op} - \eta_{DC}) \quad (9)$$

Results

Both procedures have been applied to Type A modules to determine the thermal resistance between cell and module leading to $0.054\ ^\circ\text{C}\cdot\text{m}^2/\text{W}$ for the indoor-outdoor V_{oc} comparison and $0.051\ ^\circ\text{C}\cdot\text{m}^2/\text{W}$ for the mesh grid procedure. It is remarkable the good agreement between both despite the uncertainty associated to the indoor-outdoor V_{oc} comparison caused by the strong lens temperature variation.

For the same CPV technology, the CNOCT has been obtained using eq. (10):

$$CNOCT = 47.8^\circ\text{C} + 29.5^\circ\text{C} \cong 77^\circ\text{C} \quad (10)$$

CONCLUSIONS

The paper describes methods for the thermal characterization of CPV modules or systems without special module modification for the placement of temperature sensors. They are based on a simple model consisting of two thermal resistance between cell, module and ambient temperatures.

The most novel method provides the thermal resistance between the cell and the module, this last measured at the heatsink or rear plate of the module. These procedures provide also nominal operating temperatures at concentrator standard operating conditions (CSOC): Concentrator Nominal Operating Cell Temperature (CNOCT) and Concentrator Nominal Operating Module Temperature (CNOMT).

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